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ULTRAVIOLET ASTRONOMICAL PHOTOMETRY FROM ROCKETS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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by
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SUMMARY

Astronomical photometry in the ultraviolet from rockets may be divided into two spectral regions: above and below 2000A. Commercially available photomultipliers may be used as detectors in the upper region. Until recently, however, detectors have been available for only two bands in the lower region: 1350-1040A and 1350-1225A. Gas ionization techniques are used in the latter region; usually nitric acid is the fill gas and calcium fluoride the window. The data obtained in a rocket firing on March 28, 1957, in the 1225-1350A spectral band are presented and interpreted for Orion and α Virginis.

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INTRODUCTION

The observational program in ultraviolet astronomy has, to date, relied entirely upon rockets, primarily of the Aerobee type. The rockets have been unguided, thus preventing identification of the star, or even the area of sky, to be studied. There are so few detectors, filters, and calibration techniques available for the ultraviolet portion of the spectrum that only simple types of observations have been possible. However, these limitations are rapidly being removed; in the meantime it is necessary to rely on broad band photometry for a few isolated spectral regions. Nevertheless, preliminary surveys of this type are of considerable value. They not only provide the first observations available for comparison with predictions of ultraviolet intensities, but also yield information that is essential for intelligent planning of later, more sophisticated experiments.

The data which have been acquired may be divided conveniently into two spectral regions – above and below 2000A – each of which requires its own type of detector. In the middle ultraviolet, from 3000 to 2000A, commercially available photomultipliers may be used. Various high silica glasses, chemical solutions, and doped crystals can be combined for spectral selectivity (Reference 1).

A PHOTOMETER FOR THE REGION ABOVE 2000A

A typical rocket photometer designed for the spectral region above 2000A contains a simple objective lens made of quartz or calcium fluoride, a filter, a Fabre lens, and a photomultiplier. Two views of a pair of these photometers assembled and ready for insertion into a rocket are shown in Figures 1 and 2. The objectives are mounted on a panel which becomes part of the rocket skin, while the filters, focal stops, and Fabre lenses are contained in the square cross-sections marked A and B (Figure 2). These sections also hold solenoid operated shutters to provide optical zeros during flight. Each square section is fastened to a cylinder which can be slid in and out of the front panel

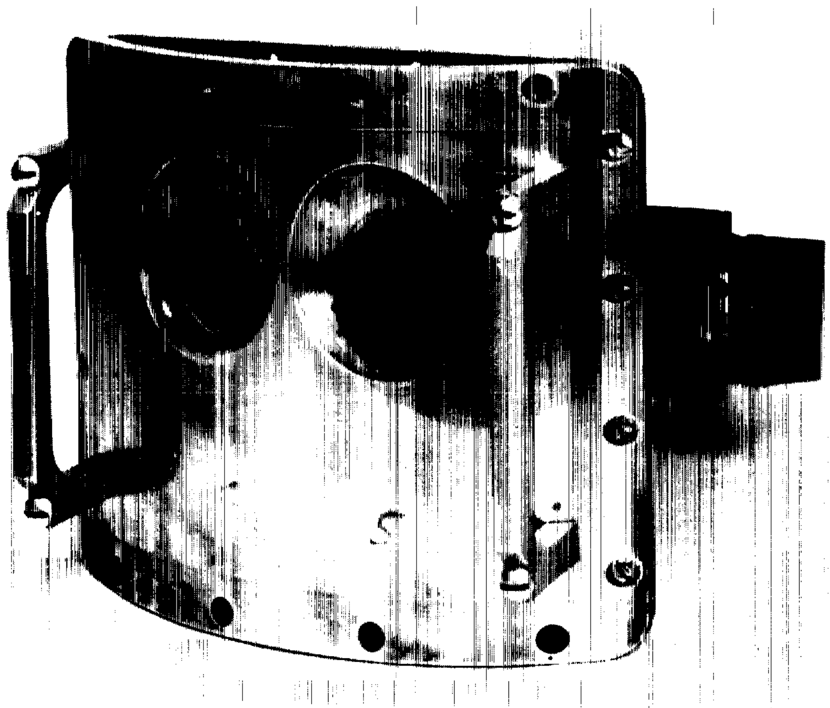

Figure 1 — Rocket photomultiplier photometers. The 2-inch quartz objective lenses are mounted in the panel, which bolts into the rocket skin. The amplifier box on the right is mounted on a photomultiplier tube projecting from the rear. The handles and protective plastic cover over the lenses are removed before flight.

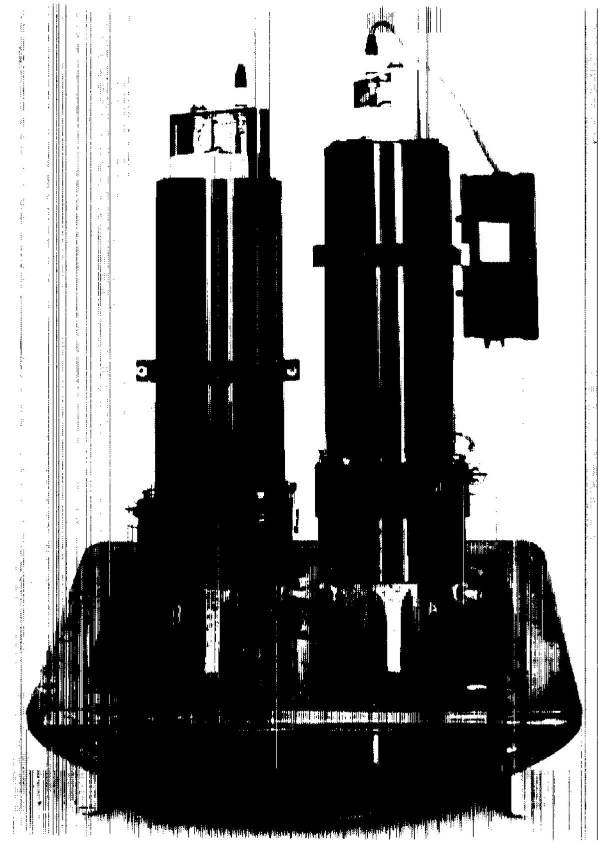

Figure 2 — Rocket photomultiplier photometers. The tubes containing filters, Fabre lenses, and photomultipliers slide in and out of the panel casting for focusing.

casting for best focus. A tube containing the photomultiplier is screwed to the back end of each unit, and the amplifier is mounted on a bracket attached to this tube. The photometers are constructed in pairs or triplets with parallel optical axes. Each photometer in the set is sensitive to a different spectral band for making simultaneous multicolor observations. The panel containing the set of photometers is inserted into an aperture in the rocket skin (Figure 3).

Several photometer sets — mounted at different positions around the rocket skin and tilted at different angles with respect to the rocket axis — are flown in each rocket so that as many stars as possible may be seen. After mounting, the angular relationships among the various photometer sets in the rocket skin are measured after they are mounted, and the photometers are calibrated. The 2537A line of mercury is a convenient photometric standard for this spectral region. Since all of the filters used thus far have had at least slight transmission at this wavelength, absolute inverse-square law calibration can be obtained by using a 2537A point source.

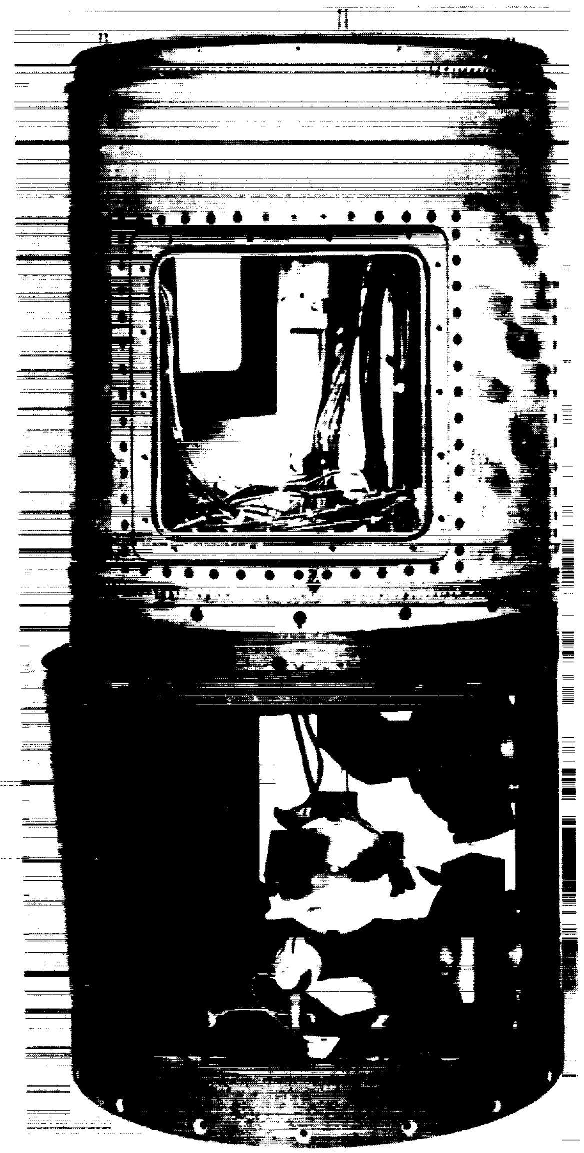

Figure 3 — Rocket instrumentation section. The upper portion is wired and ready for the photomultiplier photometers to be mounted. In the lower portion, an ion chamber in the foreground is at the focus of the mirror mounted in the rear. Two other mirror mounts are to the right, and one of the protective skin panels is shown partly ejected to the left. The nose cone, containing batteries, telemeter, etc., is bolted to the top of this section; the bottom mates to the rocket tankage.

DETECTORS FOR THE REGION BELOW 2000A

Until recently, detectors have been available for only two bands in the region below 2000A: from 1350 to 1225A and from 1350 to 1040A. The latter band including the Lyman α line at 1216A has so far been useful only for studying Lyman α radiation scattered locally within the solar system.

The 1350 to 1225A region is used for observation of stars and nebulae. Gas ionization techniques are used in this region; usually nitric oxide is the fill gas and calcium fluoride the window material. The ionization efficiency of nitric oxide at Lyman α (Reference 2) is used as the fundamental calibration standard for this portion of the spectrum. By using sodium salicylate phosphor, which has an essentially uniform response throughout this spectral region (Reference 3), the calibration is extended to other wavelengths. The spectral response curve of a detector is measured by a vacuum monochromator which alternately exposes the sodium salicylate and the detector to the spectrum of molecular hydrogen.

Photon counters have been used as detectors because of their high sensitivity, but the development of the gas-gain ion chamber has made possible the elimination of the photon counter with its stability problems and statistical uncertainty at low counting rates. The configuration of an ion chamber telescope is shown in the lower part of the rocket section (Figure 3). An ion chamber is mounted on the near side of the rocket at the focus of a 4 inch mirror placed diametrically opposite. The backs of two other mirror mounts can be seen to the right. The chambers at the foci of these mirrors are hidden from view by the protective skin panel shown on the left. The skin panels, fitted around the circumference of the rocket section during powered flight, are ejected shortly before the observing altitude is attained, both to accelerate evacuation of air from the section and to give the telescopes access to the sky.

INTERPRETATION OF THE DATA

At observing altitudes the photometers scan the sky with the combined rotational and precessional motion of the rocket. Ideally, for a survey experiment, the rocket would slowly turn end-over-end as it rotated, permitting a detector on the side of the rocket to build up an area-filling raster across the sky. Since this type of motion is rarely achieved in practice, several identical photometers are usually flown, mounted so that their scans will interlace and provide a complete survey of the sky. A preliminary solution of the rocket motion can be obtained from magnetometer data and airglow signals. A few of the brightest stars can then be identified from the telemeter records, and the final aspect solution proceeds rapidly.

Results for the Region Above 2000A

A portion of the telemeter record from one photomultiplier photometer is reproduced in Figure 4. The optical axis of this photometer was inclined 75 degrees with respect to the rocket axis. During the uppermost trace, the rocket was still rising out of the airglow layer, and the spectra of the stars may be seen superimposed on the slowly decreasing background due to the Hertzburg bands of molecular oxygen in the nightglow.

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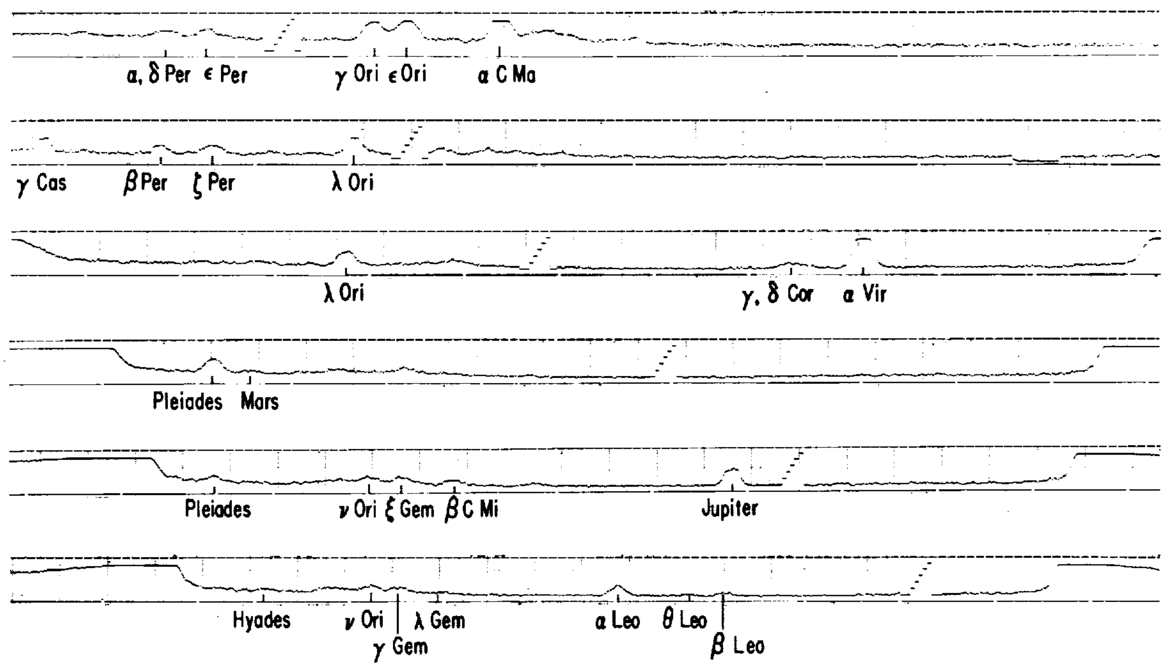

Figure 4 — Telemeter record from 2700A photometer. Saturated signals at the ends of the traces are due to the airglow horizon. Vertical timing marks represent 1/2-second intervals. Telemeter calibrations indicator 1 volt steps.

As the rocket axis tilts from the vertical, the photometer is pointed below the horizon part of the time. The saturation signals at the end of each trace are due to airglow near the horizon. With each succeeding rotation less time is spent above the horizon owing to the increasing tilt angle of the rocket.

Many stars stand out clearly on the record; for those with good clean deflections the flux in absolute units can be measured to within about 25 percent. This photometer was sensitive to a 300A band centered at 2700A. Color effects are quite marked at these wavelengths. The limiting (visual) magnitude of this photometer varied from nearly 5 for early B stars down to zero for early F stars. The first stellar observations were made in the 2700A band (References 4 and 5), since the only filter available was for this wavelength. With it, some color anomalies were observed in A stars, owing perhaps to the strong 2800A doublet of ionized magnesium lying within the filter's band. More recently, data have been obtained with filters having effective wavelengths at 2600 and 2200, and a continuing program is now underway to measure stellar fluxes at these wavelengths.

Results for the Region Below 2000A

More remarkable results have been obtained in the spectral band from 1225 to 1350A. Data on this portion of the spectrum have been collected from five flights thus far. The most successful of these occurred on March 28, 1957, when four photon counters were flown (Reference 6); a portion of the telemeter record from one of these counters is shown in Figure 5. The counter swept across the sky from west to east, its earliest trace — marked *a* — was close to the southern horizon. Each successive trace lay a few degrees north of the preceding one. No point sources can be identified on this record. Instead, bright extended areas are seen, especially near the Milky Way. In trace *a* the detector first sees radiation in the southern part of Orion and is continuously active as it scans along the galactic plane through Puppis and Vela. This trace occurred at low altitude and was significantly affected by atmospheric absorption. On succeeding traces the detector was saturated as it swept more centrally through Orion, but the adjacent Milky Way was somewhat less bright. At the right edge of scan *c* a source well away from the galactic plane is observed, and on scan *d* this source, which is in the direction of α Virginis, saturates the detector.

That portion of the sky mapped out on this flight is shown in Figure 6. This map, in equatorial coordinates, is a plot of the raw data; no correction has been applied for the atmospheric absorption which affected observations near the southern horizon. The sky, particularly the region around Puppis and Vela, is much brighter than is indicated. The most striking area is in Orion, but other regions well away from the Milky Way were discovered. The brightest of these is in the direction of α Virginis at $13^{h}_{.}4$, $-10°$; others occur at 10^{h}, $+10°$ near α and ρ Leonis and at 14^{h}, $+50°$ in the vicinity of η Ursa Majoris. Each of these regions was scanned several times during the flight, and they are well defined. The remaining areas in Figure 6 were less well observed and are generally

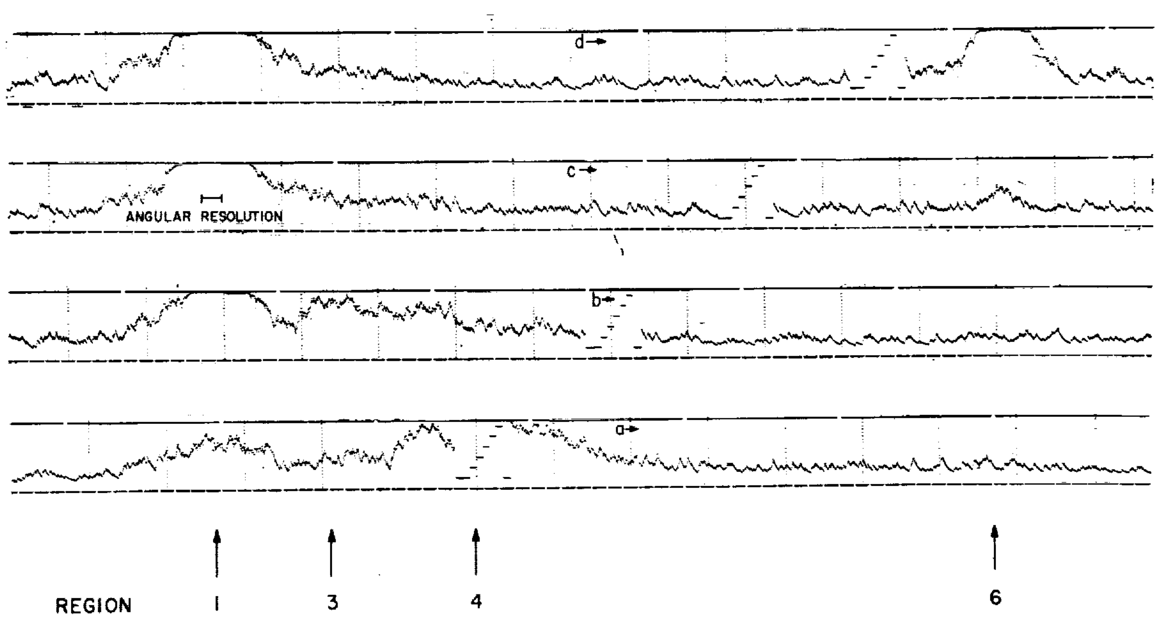

Figure 5 — Telemeter record from 1225-1350A photon counter. The saturated regions on the left are in Orion. At the right ends of scans c and d are deflections due to the α Virginis nebula. Individual counts are distinguishable at low intensities. Vertical timing marks represent half-second intervals.

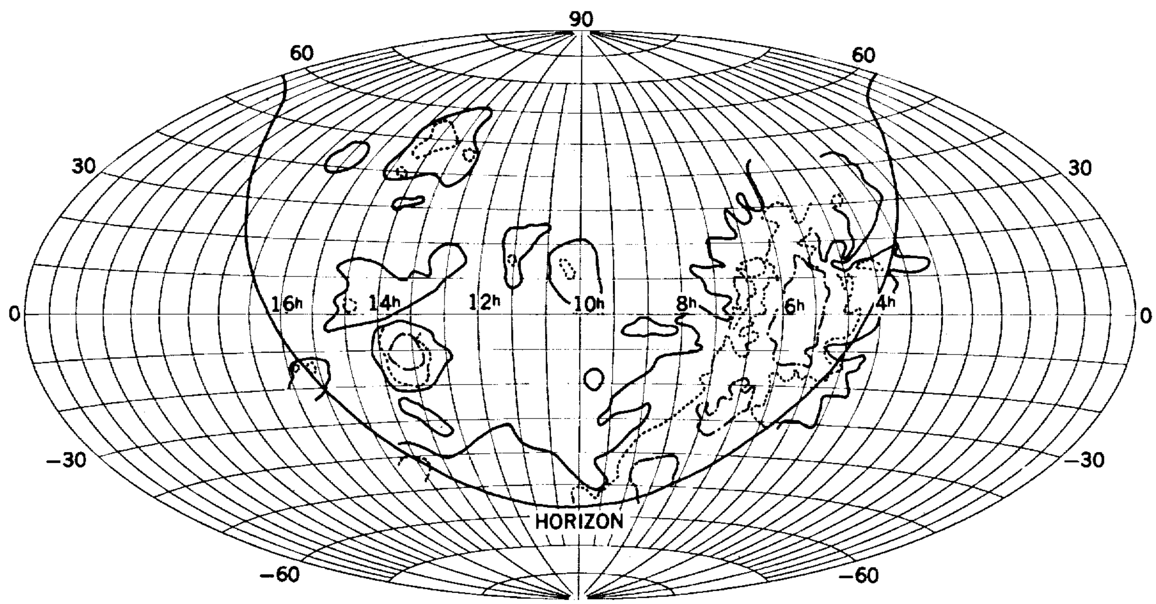

Figure 6 — Map of sky at 1225-1350A. Contours are drawn at 1.2, 2.4, and 4.8 x 10^{-4} erg/cm^2-sec per hemisphere. The heavy smooth curve indicates horizontal; the horizon is depressed about 15° at observing altitude.

fainter, although a few are quite extensive. It may be significant that none of the latter areas are in the vicinity of bright early type stars.

Figures 7 and 8 show more detailed isophotes of the Orion and α Virginis sources, which were thoroughly scanned on this flight. The greater detail shown in the Orion contours is possible since a pole of the rocket scanning motion was located in Orion, causing it to be criss-crossed with a tight network of scans. It must be remembered, of course, that contours derived from effectively random cross-sections are subject to considerable interpretational error. The details of the contours in Orion are not intended to be taken literally; rather they are an indication of the structure which is present and are comparable to the 3 degree resolution of the detectors.

In each figure, the outermost contour shown is the faintest one that is clearly separable from the background; and the innermost contour is at the saturation level of the detectors. Therefore, the central intensity distributions are not known. From the nature of the signals at saturation it appears that the central intensities in both areas can be only a few orders greater than those for the innermost contours shown. An interesting feature of the Orion region is the dark lane on the eastern edge of the nebulosity, approximately coinciding with the galactic plane, which may indicate obscuration in the plane itself. This is the only portion of the Milky Way in which a reduction in intensity has been observed, but since this is the only portion to be scanned in great detail, a slight decrease in intensity might have passed undetected elsewhere.

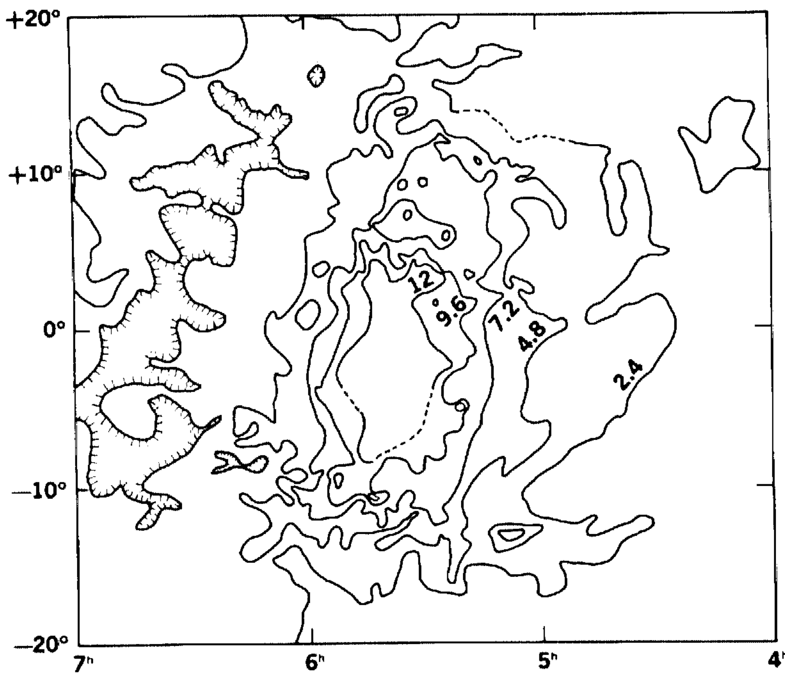

Figure 7 — Isophotes of Orion nebulosity at 1225-1350A. Ciliated contours represent intensity minima; dashed contours are inferred from incomplete data. Surface brightness is given in 10^{-4} erg/cm^2-sec per hemisphere.

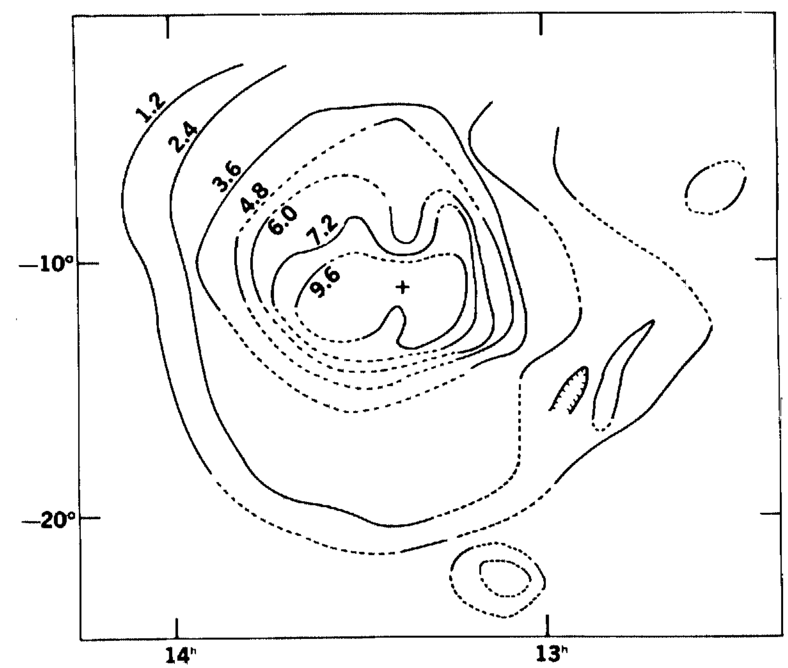

Figure 8 — Isophotes of α Virginis nebulosity at 1225-1350A. The cross indicates the position of the star within the nebula. Dashed contours are inferred from incomplete data. Surface brightness is given in 10^{-4} erg/cm^2-sec per hemisphere.

The α Virginis nebulosity shown (Figure 8) is particularly intriguing. It is well away from the galactic plane and is the brightest isolated object yet discovered. A cross indicates the position of α Virginis within the nebula; the central location of this star and the symmetry of the nebula suggest that the two may be connected. The average diameter of the nebula is about 22 degrees. The intensity gradient increases abruptly about halfway in, forming an 11 degrees in diameter core which contributes 60 percent of the radiation.

DISCUSSION OF RESULTS

The data presented herein are from a single flight — that of March 28, 1957. Nebular radiation at these wavelengths has been observed on three other flights, but they have been useful primarily as corroboration of the 1957 results. An earlier flight, in 1955, discovered the sources in Puppis-Vela, Leo, and Ursa Major (Reference 7). In this first exploratory flight the detector was very broadly collimated and yielded no information on the nature of the sources — whether they were point or extended.

Additional evidence on the size of the sources arose from a partially successful flight in May, 1960. This rocket spun at the rate of 2.2 revolutions per second, forcing the detectors to scan the sky at nearly 800 degrees per second. The rocket was also unusually stable, so that the detectors swept over only a narrow belt which included the Milky Way in Scorpio and α Virginis. At such a high scan rate, the resolution of the detector was not determined by its geometrical field (2 degrees), but by the rise time of the detector amplifier, approximately 30 milliseconds, corresponding to about 25 degrees. The slow rise time compared to the scan rate severely reduced the sensitivity of the detector, so that only the brightest sources could be seen. Also, no information about the size of the sources could be obtained from any one scan, especially in Scorpio where the many hot stars might appear as a single broad source. However, α Virginis is isolated, and the slight precessional motion of the rocket permitted the detector to see this source for 58 consecutive scans. Analysis of the rocket motion shows that near α Virginis adjacent scans were separated by 9 minutes of arc. Therefore, during the 58 scans, the detector saw the source over an angular extent of 9 degrees.

The detector was, it appears, only sensitive enough to see the brighter core of the object illustrated in Figure 8. The 1957 data were obtained with a photon counter using a geometrical collimator for spatial resolution. The 1960 flight employed an ion chamber at the focus of a 4 inch mirror (Figure 3). The significance of the latter data is due to their having been obtained with a different type of detector and a different observational technique. The extended appearance of the α Virginis source is real and cannot be attributed to a peculiarity of the instrumentation.

The data on the Orion and α Virginis nebulosities are summarized in Table 1. The calibration might be in error by as much as a factor of 2 depending on the spectral character of the radiation. The brightnesses of the saturated central regions, however, have been estimated conservatively. Since the effects of interstellar absorption were completely neglected, the total luminosities and resulting volume emissions are probably lower limits. This is especially true in the case of Orion, where there is a great deal of obscuration in the field.

Table 1
Nebular Densities at 1225-1350A

Measurement	Orion	α Virginis
Mean Surface Brightness (erg/cm^2-sec)	2×10^{-4}	1×10^{-4}
Flux at Earth (erg/cm^2-sec)	5×10^{-5}	1×10^{-5}
Luminosity* (ergs/sec)	2×10^{39}	1×10^{37}
Mean Volume Emission (erg/cm^3-sec)	4×10^{-24}	2×10^{-23}

*Based on distances of 520 pc for Orion and 87 pc for α Virginis.

α Virginis, on the other hand, has no color excess, and the reduction of nebular intensities due to interstellar absorption in this direction should be small. Evidence of the spectral character of this radiation is slight, although it is extremely unlikely that the energy is due to Lyman α radiation. The spectral sensitivity of these detectors has been carefully measured and is found to be low by a factor of 10^5 at 1216A owing to absorption by the calcium fluoride window.

In principle, some knowledge of the spectral distribution of the radiation can be obtained from the known wavelength dependence of the absorption coefficient of molecular oxygen (Reference 8), the chief atmospheric absorber in this spectral region. The mean absorption coefficient for the observed radiation can be measured as the rocket rises through the atmosphere, and the wavelength corresponding to this absorption coefficient is the spectral centroid of the radiation. In practice, any one source is rarely seen often enough during a flight to determine an absorption coefficient. Data for both the 1955 and 1957 flights indicate that the spectral centroid may lie between 1260 and 1280A and that the radiation is confined to a rather narrow spectral band or may even be monochromatic. However, these conclusions are based on insufficient data and should be treated with caution.

The emission of such large amounts of energy in the 1225 to 1350A band is difficult to explain. There is no indication of any nebulosity around α Virginis at visual wavelengths. Furthermore, the density of interstellar material in this direction is thought to be low (Reference 9). What is required is an abundant, efficient ultraviolet radiator which is undetectable in the visible. The material most likely to fulfill this requirement is molecular hydrogen. Certainly it cannot be detected by conventional observations and may well be abundant in interstellar space. Molecular hydrogen might emit energy in the 1300A region in two ways: (1) the Lyman bands can be emitted by scattering and fluorescence of the stellar Lyman α and continuum; and (2) Krook has pointed out that Raman scattering of Lyman α by molecular hydrogen produces a line within the band. The latter suggestion has some support from the evidence that the radiation may be narrowly concentrated at wavelengths acceptably close to the Raman line. Unfortunately, none of the mechanisms suggested offers a satisfactory quantitative explanation of the observed energy.

Also of considerable interest in the results of the 1957 flight is that point sources were not observed. In fact, every bright early-type star which might have been detected was surrounded by nebulosity. The best example is α Virginis, which was not seen even though two of the detectors swept directly across the star. One characteristic of the photon counters is that they will reverse under the influence of strongly saturating stimuli in a manner analogous to the reversal of a photographic emulsion. Since a reversal did not occur when the already saturated detectors were pointed towards α Virginis, an upper limit can be placed on the stellar flux—2×10^{-7} erg/cm^2-sec in the 1225 to 1350A band. This upper limit is an order of magnitude less than is predicted by the model atmosphere for α Virginis.

Although it was tempting to consider the deficiency of stellar energy was due, in some way to the nebular radiation, this no longer appears to be the case. In June, 1960, a rocket was flown carrying an ion chamber telescope sensitive to the 1225 to 1350A region. The attitude of the rocket was such that the only bright B star that could be seen by the detector was ϵ Persei. In this case the star itself was observed and no surrounding nebulosity was detected. The measured flux was 10^{-7} erg/cm^2-sec, again approximately an order of magnitude less than indicated by the stellar models. This observation, the most recent information obtained in the 1225 to 1350A band, indicates that not all early B stars are associated with extended ultraviolet emission regions, but that early B stars as a class may be inherently less bright than the model atmospheres predict.

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